ON THE DIFFERENTIATION OF DIFFUSION BOND STRENGTH USING THE TOTAL ACOUSTIC ENERGY REFLECTED FROM THE BOND

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INTRODUCTION

Diffusion bonding is a well known metallurgical joining technique which allows similar and dissimilar materials to be bonded together in near net shape. Due to this feature, wider use of this technique is now being made, especially in aerospace industries. Therefore, the differentiation of diffusion bonds with little variation in their acoustic response is of critical importance since relatively significant changes in bond strength may be a consequence. The challenge at the present time is to find ultrasonic techniques that are sensitive enough to detect small changes at the original interface. A number of diffusion bonds has been made that shows only a slight variation in a single frequency reflection measurement with significant changes in the bond strength. Present work indicates that an energy measurement can differentiate the strength achieved in these diffusion bonds. This evaluation procedure is based on Parseval's theorem [1] which states that the energy in the time domain is proportional to the energy in the frequency domain. The results of earlier measurements on Cu against Cu [2,3] are reanalyzed and compared with those obtained recently on Cu against Ni [4,5] as well as Ti-6Al-4V against Ti-6Al-4V. It is found that the sensitivity of the normalized energy measurements to changes in the bond strength is enhanced over single frequency reflection coefficient measurement and that the energy reflected is mainly originating at the voids still present in the original interface.

EXPERIMENTAL PROCEDURES

Diffusion bonds of Cu against Cu and Cu against Ni, obtained under a variety of conditions, as described in [2-5] were evaluated acoustically in a water bath using a broadband 2 to 15 MHz (10 MHz center frequency) focused transducer with longitudinal polarization in normal incidence and back reflection [2]. In addition, a series of Ti-6-4 diffusion bonds were produced over a temperature range of 750 to 900° C and a bond time range of 0.25 to 4h at a pressure of 18 MPa. Pulse-echo scans were performed along the diameters of all bonded samples at 30° rotation intervals, with data taken at 0.64-mm increments along each diameter. After scanning, a diamond saw slot was cut just above the interface to simulate a perfect reflector. The reference signal from this reflector incorporates the microstructure of the material. After capturing these acoustics signals, four tensile specimens were cut from each diffusion-bonded sample [2], with the long specimen axis

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perpendicular to the bond plane and dimensions of 25 mm x 6.5 mm x 6.5 mm. Final dimensions of the gage sections were 6.5 mm x 2.5 mm. The tests were performed using an Instron mechanical testing machine at a strain rate of 1.3×10^{-3} sec^{-1}, providing information on the ultimate (tensile) strength of each specimen interpreted as the bond strength. This approach is certainly conservative since the reduction of area has been found to be as large as 25% so that the true bond strength can be appreciably larger.

ACOUSTIC EVALUATION

To determine reflection coefficients, the time domain signals received from the bonded areas, as well as from the reference signals, were Fourier transformed to their respective frequency spectra. The ratio of the bond signals to the reference signal then provided reflection coefficients as a function of location and frequency of the diffusion bonds. This evaluation provides "contour maps" over the full diameter of the diffusion bonds, as given in Ref. [2]. Each tensile specimen's individual reflection coefficient was determined as the average reflection coefficient at the location from which the specimen was taken. This procedure yields an error of at least ±0.01 in the reflection coefficient. In the case of Cu-Cu diffusion bonds and selecting the reflection coefficient at 10 MHz, this scheme provided a reasonable correlation [2] of the tensile strength versus reflection coefficient, except for the strongest bonds where the error becomes relatively large with respect to the absolute value of the reflection coefficient. However, the increase of the reflection coefficient with frequency for each specimen was found to be consistent with theory [6], although the same scatter as above was noted judged from best fit curves to the data.

Performing the same scheme on Cu-Ni diffusion bonds, it was immediately recognized that the above evaluation scheme provides for rather unsatisfactory results since even weak bonds did not yield a significant enhancement of the reflection coefficient over the theoretical value due to the impedance mismatch between Cu and Ni [4,5]. Therefore it was suggested to use Parseval's theorem [1], which basically averages the square of the reflection coefficient over the total frequency range, providing a "normalized energy" reflected from the bond. To be more precise, Parseval's theorem states that the energy of the wave at the time domain is equal to the energy in the frequency regime

$$\int_{-\infty}^{+\infty} [g(t)]^2 dt = \int_{-\infty}^{+\infty} [G(f)]^2 df \qquad (1)$$

where $G(f)$ is the Fourier transform of $g(t)$. Therefore, this normalized energy is basically proportional to the square of the reflection coefficient, favoring the high frequency end of the available acoustic spectrum. Thus, higher sensitivity to any change in the reflection coefficient is expected. In the present case, six signals at the intersection of the pulse-echo scans were used to determine the normalized energy reflected from each bond. Before performing the procedure outlined in Eqn. (1), the signals were averaged in the time domain and the signal background noise subtracted.

RESULTS AND DISCUSSION

Figure 1 shows a comparison of selected data obtained on relatively strong Cu-Cu diffusion bonds [2]. Obviously, the scatter band in the normalized energy data (Figure 1b) is improved over that in the reflection coefficient data at 10 MHz (Figure 1a). As the bond strength of the diffusion bonds drops from the highest value achieved (210 MPa) to about half the maximum strength (135 MPa), the normalized energy increases by at least a factor of five (Figure 1b), whereas the reflection coefficient itself increases by at most a factor of three (Figure 1a), which is still within the scatter band of this evaluation scheme. Thus, the theoretically expected sensitivity increase in the measured normalized energy over that in the reflection coefficient is, roughly, verified.

Similar results have been found on diffusion bonds of commercial Ti-6-4, as shown in Figure 2. Although the reflection coefficient measured shows the expected trend with bond strength (Figure 2a), the normalized energy data provide a significant improvement of the correlation with the bond strength data as shown in Figure 2b. All bonds with a strength of 700 MPa or below are clearly separated from high strength bonds (at about 950 MPa). As in the case of Cu-Cu diffusion bonds, discussed above, a drop of the strength from 950 MPa to about half the value (450 MPa) increases the energy reflected by about a factor of five. We therefore conclude that the energy reflecting defects are basically the same in both materials which have been clearly defined as voids in the Cu-Cu diffusion bonds [2,3].

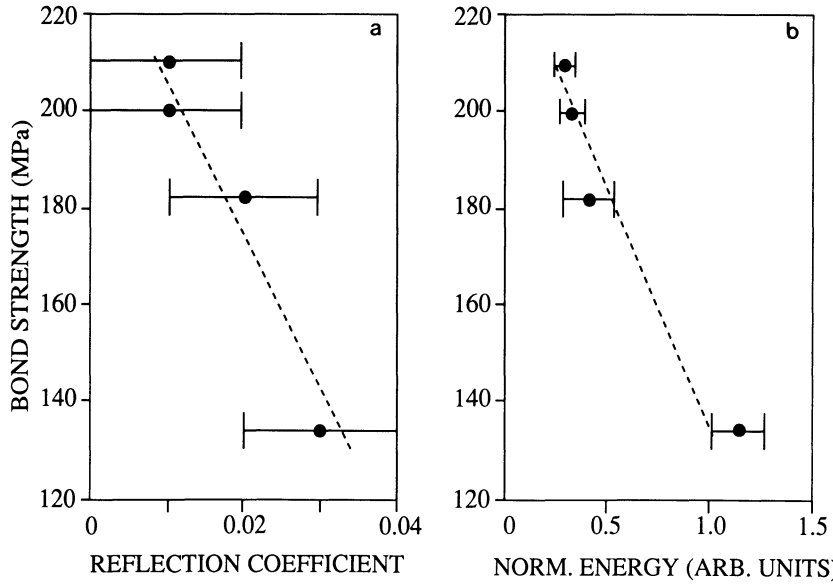

Figure 1 Bond strength of Cu-Cu diffusion bonds (data from Ref. [2]), a.) versus reflection coefficient (at 10 MHz); b.) versus normalized energy.

Extracting such information is significantly more difficult on diffusion bonds produced from dissimilar materials such as Cu against Ni, since the acoustic impedance mismatch between the two materials yields a background signal on top of the signals reflected from the ingrown defects. The situation is further complicated by the interdiffusion of one metal into the other, producing an alloy which by itself may strongly affect a signal, even if no voids are left during the diffusion process. By choosing Cu and Ni, we tried to avoid this latter problem as much as possible in that Cu, Ni, as well as the resulting CuNi alloy are all of the same crystal structure (face-centered cubic). As was shown [4,5], the resulting CuNi alloy reduces the reflection coefficient with increasing thickness of the interdiffusion region from the theoretical value of the impedance mismatch. Yet, in spite of the expected difficulties, normalized energy measurements provide information on the achieved bond strength, as shown in Figure 3. In this case, six samples were investigated, three produced at a bond

pressure of 13.3 MPa and three at 18.8 MPa. Measurements were taken both from the Cu and the Ni sides of the diffusion couples. If plotted against the achieved bond strength, all normalized energy measurements taken on the Ni side were consistently higher than those taken on the Cu side of the couples. However, each grouping showed a correlation with the achieved bond strength, as indicated by the two dashed lines in Figure 3. The reason for the discrepancy in the normalized energy switching from the Ni side to the Cu side is not quite clear at the present time. Any effects due to the differences in the microstructures of the two materials (grain size, e.g.) should not be significant in that in both cases, use was made of a reference signal from a saw slot. However, the saw slot does eliminate a microstructural

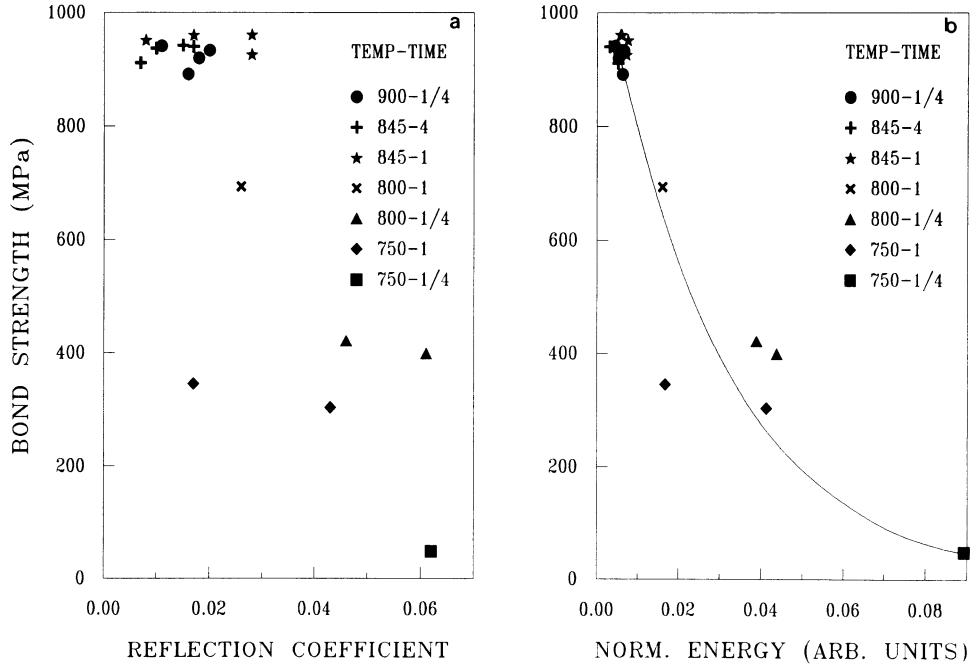

Figure 2 Bond strength of Ti-6-4 diffusion bonds, a.) versus reflection coefficient (at 10 MHz); b.) versus normalized energy.

feature caused by the interdiffusion. Ni diffuses much more readily into the Cu than Cu diffuses into the Ni. This produces a very uneven boundary between Cu and the developing CuNi alloy, whereas the boundary between Ni and the CuNi alloy stays relatively plain. This microstructural feature is shown in Figure 4 in the form of a micrograph of a sample bonded at 650° C for 4h at 18.8 MPa, resulting in a bond strength of 200 MPa and a relatively large change in the measured normalized energies. The unevenness of the Cu/Ni boundary decreases with bond temperature and time (leading to lower bond strength) and, as expected, the relative change between the measured normalized energies becomes smaller. We thus conclude that this unevenness (roughness) produced on the Cu side of the diffusion couples leads to ultrasonic scattering which reduces the normalized energy in the Cu-side measurements, as discussed earlier [5,7]. Further studies are necessary, however, to verify this tentative explanation.

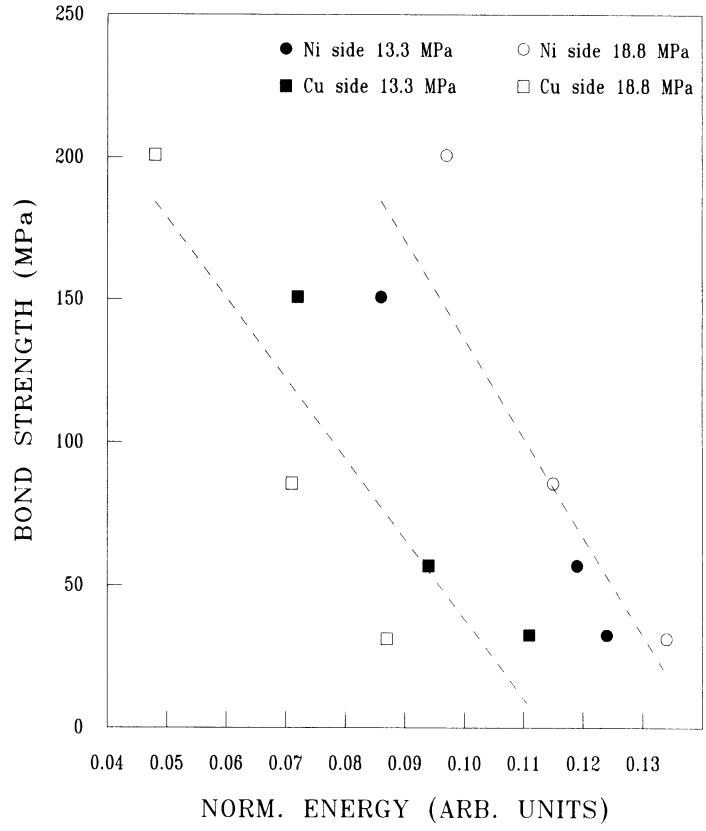

Figure 3 Bond strength of Cu-Ni diffusion bonds versus normalized energy as measured from the Ni and Cu sides of the diffusion couples (date from Ref. [4]).

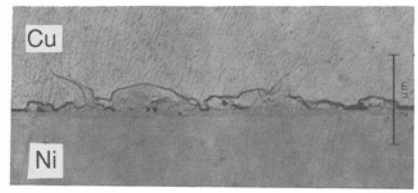

Figure 4 Optical bond line micrograph of the interdiffusion region in Cu-Ni.

CONCLUSIONS

Single frequency reflection coefficients as well as the energy reflected over a broad acoustic frequency band (2-15 MHz) as well as their mechanical bond strength have been evaluated on a variety of diffusion bonds. The results indicate that energy data are more sensitive to small bond strength changes as theoretically expected from Parseval's theorem. In all cases, the energy reflected is mainly originating at the voids still present at the location of the original interface. In addition, other microstructural features that are caused by the interdiffusion appear to diminish the energy reflected due to scattering of the interrogating acoustic wave.

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